Networks and innovation in a modular system: Lessons from the microcomputer and stereo component industries

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In this paper we examine theoretically and through case studies the phenomenon of the modular system, which we distinguish from a product conceived of as a prepackaged entity or appliance. We argue that such systems offer benefits on both the demand side and the supply side. Supply-side benefits include the potential for autonomous innovation, which is driven by the division of labor and provides the opportunity for rapid trial-and-error learning. Demand-side benefits include the ability to fine-tune the product to consumer needs and therefore blanket the product space more completely. Both of our case studies suggest that innovation in a modular system can lead to vertical and horizontal disintegration, as firms can often best appropriate the rents of innovation by opening their technology to an outside network of competing and cooperating firms. We conclude by speculating on the increased importance of modular systems in the future, since flexible manufacturing and rising incomes are likely to increase the driving requisites of modular systems: low economies of scale in assembly and sophisticated consumer tastes.

Introduction

The degree of vertical integration in an industry depends on both supply and demand conditions. In this paper, we explore the relationship between supply and demand conditions in shaping the nature of an industry and the scope of activities of specific firms.

The effects of such supply factors as the division of labor, economies of scale, and the presence or absence of external economies have been thoroughly explored over a period of more than 200 years. Demand factors have received less attention. In particular, the tendency of economists to assume product homogeneity has obscured the fact that the structure of an "industry" and the characteristics of the firms it comprises can vary greatly depending on how consumers define its "product." Over time, the nature of what consumers believe is the essence of a given product often changes. Consumers may add certain attributes [1] and drop others, or they may combine the product with another product that had been generally regarded as distinct. Alternatively, a product that consumers had treated as an entity may be divided into a group of subproducts that consumers can arrange into various combinations according to their personal preferences.

We call this kind of network of subproducts a *modular system*. The nature of an industry and the extent of vertical integration therefore depend not only on what patterns of production minimize production and transaction costs, but also on which attributes consumers may wish. As a result of "bundling," "unbundling," and "rebundling" various attributes, the definition of a

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[1] In the sense of Lancaster [11]. We discuss this approach in greater detail below.

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product and the structure of the industry that manufactures it may change dramatically.

Recently, formal price theory has turned its attention to some of the demand-side aspects of modular systems. But this literature does not simultaneously address the supply-side issues of technology, innovation, and firm boundaries.[2] Our objective in this paper is to look at both sides of the market. On the demand side, we look at how autonomous changes in consumer tastes and the reaction of consumers to changes introduced by suppliers help to shape the definition of a product. On the supply side, we consider the importance of technical and organizational factors in influencing the production cost, and therefore the price to consumers, of employing various degrees of vertical integration. We also recognize the vital role of suppliers as innovators who can bring new components and new arrangements of existing components to the notice of consumers.

This first section of the paper outlines the theoretical underpinnings of the relationship between vertical integration and desired product attributes. The next two sections examine these concepts through case studies of the stereo component and microcomputer industries.

Attributes and product differentiation

For most kinds of products – toasters or automobiles, say – manufacturers offer preset packages. One can choose from a multiplicity of packages, but one can't choose the engine from one kind of car, the hood ornament from another, and the front suspension from a third. Not only are there transaction costs of such picking and choosing (Cheung [3, pp. 6–7]), there are also economies of scale in assembling the parts into a finished package. Indeed, it is these economies of scale more than transaction costs that explains the tendency of assemblers to offer preset packages. If there were only transaction costs of discovering which parts are available and what their prices are, we would expect to see not preset packages but a proliferation of middlemen who specialize in packaging components tailored to buyers' specific tastes. For most appliance-like products, however, the economies of scale of assembly lead to integration of the packaging and assembly functions.

One way to think about this is in terms of the modern theory of product differentiation.[3] Instead of seeing a product as an ultimate entity, view it instead as an input (or set of inputs) to the production of utility through the consumer s "consumption technology" (Lancaster [11]). In technical terms, the consumer chooses among available bundles (or combinations of bundles) to reach the highest indifference surface possible. Each bundle represents a location (technically speaking: a vector) in "product space," and each consumer has a preferred place in that space – a bundle with his or her favorite combination of attributes. If there are scale economies, some producers can gain advantage by choosing the locations in this space where they think the density of demand will be highest. An example of this is Ford's Model T. The undifferentiated, no-frills product may not have suited everyone's (or, indeed, anyone's) tastes exactly. But the progressive reductions in price that long production runs made possible brought the Model T within the budget constraints of a growing number of people who were willing to accept a relatively narrow provision of attributes rather than do without.[4]

In the extreme case of no economies of scale, the entire space can be filled with products, and

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[2] The work most relevant to our concerns is that of Matutes and Regibeau [16], who cast the problem of "mix and match" in the form of a game. In this model, two firms who produce a two-component system must each decide whether to make parts compatible or incompatible with those of the competitor. Apart from being rather stylized, however, this model does not look at the issue of vertical integration, assuming instead that both firms produce both components. The model also does not examine the effect of the compatibility decision on innovation or production costs.

[3] For a straightforward introduction, see Waterson [30, chapter 6].

[4] Although price factors can be important, we must be careful not to place too much emphasis on them. Poor or unsophisticated consumers will be much more susceptible to low-cost products cave lower budget constraints); but, as incomes and sophistication increase, a higher proportion of buyers will seek a better selection of attributes. A sufficient number of people were able to afford better bundles of attributes that, even at the peak of its popularity, the Model T did not force Cadillac, Lincoln, or Packard from the market. And, as incomes rose generally in the 1920s, the Model T itself succumbed as a higher proportion of consumers had the means to purchase superior selections of non-price features (Langlois and Robertson [14]).

each consumer can have a product tailored exactly to his or her requirements. The type of product we have called a modular system approximates this extreme: both the transaction costs of knowing the available parts and the scale economies of assembling the package are low for a wide segment of the user population. By picking and choosing among an array of compatible components, the consumer can move freely around a large area of the product space.

In the case of sound reproduction, for example, the list of attributes can be extensive and the tradeoffs among them complex. The product technology the consumer chooses is a function of the attributes sought. As the range of the voice is limited, high fidelity can be achieved more easily for voice than for music: in contrast to lovers of piano sonatas, consumers who confine their listening to news broadcasts can get by easily with small radios and have no practical use for a sophisticated combination of components. When immediacy is needed, a radio or telephone will provide better service than a phonograph. The ability to store sound, on the other hand, can be accomplished using a record, tape, or compact disk, but not directly by a telephone or radio. When reciprocal communication is wanted, a telephone suits the purpose while a radio receiver does not.

When the bundle of overlapping attributes for different consumption technologies is small or they conflict in some way, consumers will use different appliances or systems. Although there are considerable technical similarities between the telephone and radio voice transmission, the differences have been more significant, ensuring that two distinct networks and sets of reception appliances have remained in use. Where attributes do not conflict, however, the presence of a high degree of technological convergence will open the way for the development of multipurpose appliances or modular systems, as in the case of a stereo set featuring several sound media that share amplification and reproduction equipment. Again, compatibility is crucial. Producers may have an incentive to create proprietary products in an attempt to capture sales of most or all potential subcomponents. But, as we suggest below, such a strategy often backfires, and the high demand that unbundling allows can often force a compatible modularity on the industry.

Thus innovation can affect consumption technology in two major ways. First, new products can satisfy a desire for attributes that has not yet been satisfied or, perhaps, even noticed. Second, through technological convergence, new ways of packaging or bundling consumption technology, and therefore providing attributes, become feasible.

For example, there may be five components involved in the production of a particular good, the famous widget (fig. 1a). Through a form of technological convergence, [5] two new components developed in other industries may turn out to be desirable adjuncts to the original good (fig. 1b). The question is, will these new components be supplied by outside firms, perhaps their original manufacturers, or will they be internalized through vertical integration by the widget makers? The answer, as usual, will depend on the extent of economies of scale and the transaction costs involved. If the minimum efficient scale (MES) of production of the new components exceeds the needs of any individual widget maker, then the component manufacturers are likely to remain independent as long as the transaction costs of dealing with outside suppliers are smaller than the additional production costs the widget firms would incur by producing at less than MES. [6] (Williamson [31, chapter 4]).

Suppose, however, that the new components are not necessary – that they may, in fact, be superfluous or even repugnant to many widget

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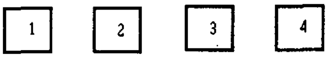
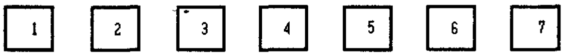
[5] On which see Rosenberg [25, chapter 1].

[6] Neoclassical economics has taught us to think of MES as a matter of technology independent of the firm using the technology. In fact, of course, production cost is an extremely firm-specific matter. As Nelson and Winter [20, chapters 4 and 5] suggest, production is a matter of the skills a firm possesses; and such skills are often inarticulate and learned gradually over time. The firm's cost of internalizing a given activity will depend on how appropriate to the task the firm's skills are, which often means how similar the activity is to the activities the firm already engages in (Richardson [22]). One force for vertical specialization, then, is the dissimilarity among stages of production. The skills necessary to make turntables may be significantly dissimilar from those needed to make amplifiers; the skills applicable to making disk drives may be significantly dissimilar from those needed to fabricate semiconductor memories. One might indeed go so far as to wonder whether such dissimilarity does not increase with the complexity and technical sophistication of the final product.



a. Components of the original widget.



b. Components of the improved widget.

Fig. 1. Producing the improved widget.

users. In this case, the decision to purchase them could be delegated to the users rather than to the widget manufacturers. Users would buy the same type of widgets that they had traditionally purchased and then, if they wished, buy one or both of the additional components, perhaps from a different shop. The production of new widgets would then come to resemble fig. 2. Alternatively, the rate of technological change of the various components that make up the widget may vary. Component 4, for example, might enter a new phase of rapid development while the remaining inputs do not vary. Furthermore, customers might have reason to believe that this component would continue to improve dramatically for some years. They would then wish to purchase a widget that embodies the traditional components 1, 2,3, and 5, but that offers the opportunity to upgrade component 4 as improved variations come on the market.

Again, whether component 4 would be manufactured by the widget maker or by someone else would depend on the relationship between production costs and transaction costs. If the widget firm decides that internalization is impractical, the situation in fig. 3 would arise. Customers would purchase component 4 separately and the remainder as a package. This assumes, of course, that the new variant is compatible with the other components. The established widget firms will have an interest in trying to avoid compatibility so that they can continue to sell the existing models that embody all five components. But the developers of the new variant of component 4 will want to achieve compatibility to allow consumers to adopt their product without fuss. In fact, if possible, the component developers will want to achieve compatibility with the products of all widget manufacturers.

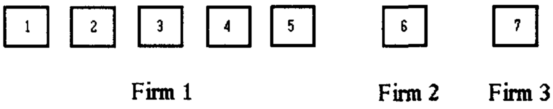


Fig. 2. Firms involved in the production of improved widget.

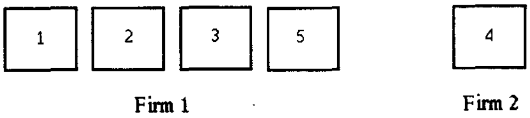


Fig. 3. Production of widgets with changing component 4.

In the situations portrayed in figs. 2 and 3, customers are no longer purchasing an appliance as they were in fig. 1. Instead, they have moved to a modular system in which they can take advantage of interchangeable components rather than having to accept an entire package that is prechosen by the manufacturer.

Networks

The vertical specialization that modular systems encourage leads also to the establishment of networks of producers. Two basic types of networks among firms are possible. The first (fig. 4) is a centralized one in which suppliers are tied to a "lead" firm, as in the Japanese automobile industry. *Decentralized networks*, however, of the type illustrated in fig. 5, are of more interest to the argument developed here (Best [1]).

W_1, W_2, and W_3 are the users of modular systems, which they assemble according to their

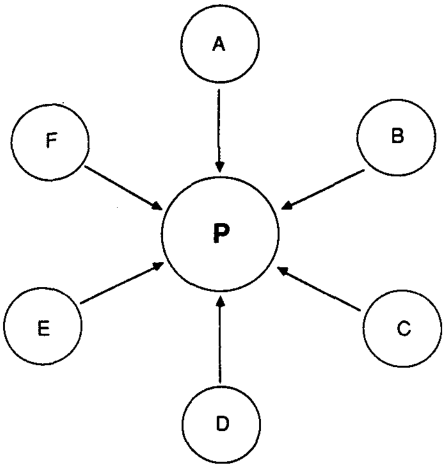


Fig. 4. A centralized network.

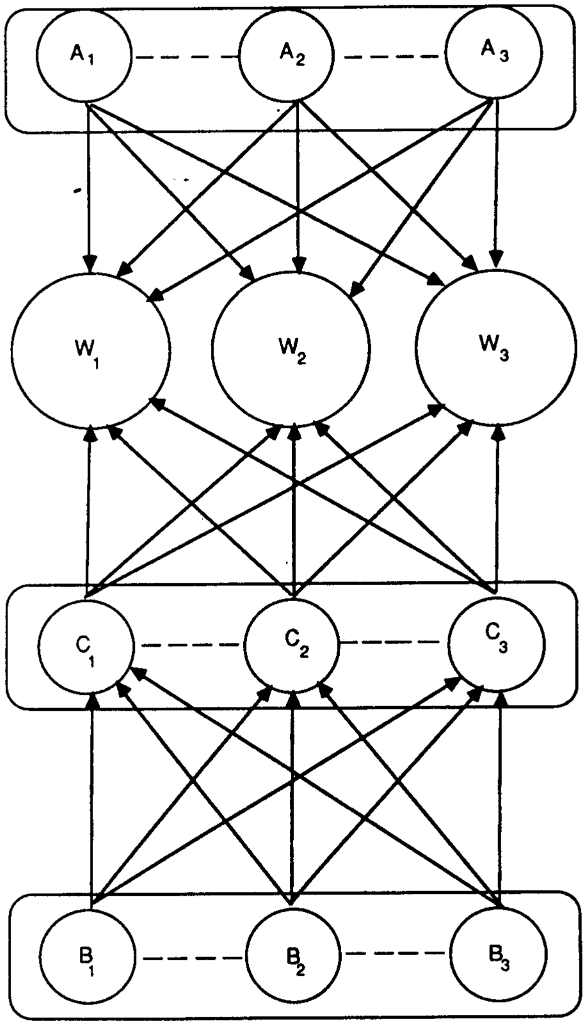


Fig. 5. A decentralized network.

individual requirements. A_1, A_2, A_3, C_1, C_2, and C_3 are the manufacturers of A and C, two of the components of systems of type W, and B_1, B_2, and B_3 are makers of subassemblies used in component C. Makers of components A and C must, therefore, ensure compatibility with each other's products and with other potential components if their output is to be suitable for modular systems of type W. But subassembly B needs to be compatible only with component C and not directly with other components.

Taken together, all of the component manufacturers (A, C) and the ultimate users (W) make up a decentralized network. In contrast to centralized networks, in which the standards of compatibility are laid down by the lead manufacturers and may differ from one lead firm to another, in decentralized networks the standards are determined jointly by components producers and user/assemblers through market processes or negotiation. No single member of the network has control, and any firm that tries to dictate standards in a decentralized network risks being isolated if users and other producers do not follow. Even component variations that are demonstrably superior in a technical sense may be disregarded if users and other manufacturers are "locked in" to existing standards because the costs of change would be greater than the benefits permitted by the new variation (David and Bunn [4]).

A second type of network is important here. Even when there is no patent or other protection, horizontal networking of firms – for example, among A_1, A_2, and A_3 or C_1, C_2, and C_3 – can allow an innovator to earn higher profits than if it attempted to appropriate all of the benefits itself. As we suggest in the case studies, when a component maker (especially of software) is unable by itself to offer customers enough variety to justify the purchase of the associated components in a modular system, the most successful firms will be those that abandon a proprietary strategy in favor of membership in a *network of competitors* employing a common standard of compatibility.

Autonomous versus systemic innovation

The benefits of modularity appear on the producer's side as well as on the consumer's side. A modular system is open to innovation of certain kinds in a way that a closed system – an appliance – is not. Thus a decentralized network based on modularity can have advantages in innovation to the extent that it involves the trying out of many alternate approaches simultaneously, leading to rapid trial-and-error learning. This kind of innovation is especially important when technology is changing rapidly and there is a high degree of both technological and market uncertainty (Nelson and Winter [19]). In a decentralized network, there are many more entry points for new firms, and thus for new ideas, than in a vertically integrated industry producing functionally similar appliances. To this extent, then, a modular system may progress faster technologically, especially during periods of uncertainty and fluidity.

Another reason that innovation may be spurred on by modularity lies in the division of labor. A network with a standard of compatibility promotes autonomous innovation, [7] that is, innovation requiring little coordination among stages. By allowing specialist producers (and sometimes specialist users) to concentrate their attention on particular components, a modular system thus enlists the division of labor in the service of innovation. We would expect innovation to proceed in the manner Rosenberg [25, p. 125] and Hughes [9] suggest: with bottleneck components – those standing most in the way of increased consumer satisfaction – as the focal points for change.

Systemic innovation would be more difficult in a modular system, and even undesirable to the extent that it destroyed compatibility across components. We would expect, however, to see systemic innovation *within* the externally compatible components. The internal "stages of production" within a modem or a tape deck can vary greatly from manufacturer to manufacturer so long as the component continues to connect easily to the network. [8] The components may, in other words, be appliances. To the extent that the coordination this internal systemic innovation requires is costly across markets, we would expect to see greater vertical integration by makers of components than by purveyors of the larger systems.

The development of high-Fidelity and stereo systems

The evolution of modular high-fidelity and stereo component systems in the post-World War II period resulted from two separate but related developments. [9] The first, the spread of an underground movement for greater fidelity in reproduction, involved better recording techniques and superior reproduction equipment. The second was the introduction of 33- and 45-rpm records and the associated use of vinyl, which greatly enhanced the usefulness of recordings, particularly for lovers of classical music. Thus the connection between changes in hardware (the components) and software (records and later tapes and compact disks) was established from the beginning.

Early developments

Before the 1930s, the phonograph [10] was an appliance. Records were still recorded and played back acoustically, using mechanical vibrations to cut grooves into wax originals and to transmit sound from records to listeners via a horn. Although various instruments operate over a range of approximately 20 Hz to 20,000 Hz, from the lowest note on the organ to the highest overtones of the oboe, acoustic records generally reproduced a range of 350 to 3,000 Hz [7, September 1939, pp. 74–75, 92; 21, p. 237; 10, p. 29].

The origins of modularity in subsequent decades can be traced to the development of the Brunswick Panatrope. Although there had been earlier radio-phonograph combinations, they were essentially two appliances encased in a common cabinet, since radio signals could not be reproduced acoustically [21, pp. 268–269]. The Panatrope, which had a vacuum-tube amplifier and a speaker, therefore permitted technological convergence, since both radio signals and signals transmitted from the phonograph pickup were now reproduced identically. This soon led to a degree of modularity, as record players could be played through a radio's amplifier.

However, significant improvements in fidelity did not occur before the end of World War II. As late as 1945, most records cut off at 8,000 Hz because of distortion in the higher ranges. This limited span was further truncated by contemporary phonographs, which seldom reproduced sounds above 4,000 Hz. American record and phonograph manufacturers of the interwar period resisted attempts to improve the range of their products on the grounds that their customers preferred a diluted sound. One survey, conducted

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[7] The notions of autonomous and systemic innovation are borrowed from Teece [27].

[8] For example, the relationship between the manufacturers of subassembly B and those of component C in fig. 5.

[9] For a fuller discussion of the early development of modular stereo sets, see Robertson and Langlois [24].

[10] A phonograph included all the equipment necessary for reproduction. With the advent of electric models in the late 1920s, this meant a speaker and an amplifier as well as the turntable. A record player was only a turntable and had to be plugged into a radio. Finally, a "combination" included both a radio and a phonograph in a single unit.

by the Columbia Broadcasting System, indicated that, by a margin of more than two to one, listeners liked standard broadcasts of up to 5,000 Hz better than wide-range programs that went up to 10,000. If, as it appeared, the most discerning of listeners were content with a cut-off of 5,000 Hz, there seemed to be no reason to improve recordings or equipment [7, October 1946, p. 161; 21, pp. 346–347].

The move toward systems in the postwar period

Even before the war, there was a move for greater fidelity among some enthusiasts. The most famous of these was Avery Fisher, who in 1937 began to produce high-quality radio sets. The high-fidelity movement gained impetus during World War II when U.S. servicemen stationed in Europe became aware of the extent to which America lagged in both record and phonograph technology. In addition, many servicemen were trained in radio or electronic technologies that were transferable to high-fidelity uses, and some brought back equipment with them [5, pp. 76–77; 21, pp. 333, 347–348; 18, pp. 62–64]. When their suggestions for improvement were rebuffed by the established firms, a number of them set up as components manufacturers.

While a few manufacturers like Fisher, Capehart, and Scott did produce high-quality phonographs and combinations in the immediate postwar years [7, October 1946, pp. 190, 193, 195], there was a movement from integrated appliances to components that resulted from both supply and demand conditions. Many of the new firms were run by specialists who could not afford to manufacture across a broad scale even if they bad had the expertise. On the demand side, interest in modularity was fueled by rapid but uneven rates of improvement across components that encouraged buyers to maintain the flexibility to update. The individualistic and subjective nature of "fidelity" also encouraged a proliferation of components as buyers sought to build systems to suit their idiosyncratic preferences. [11]

Components in the sense of add-on equipment had been available for many years. In 1933, for example, RCA began to offer the Duo Jr. record player that could be played through a radio. Available for $9.95, it was part of a successful attempt to revive the sale of records during the Depression. In general, the "war of the speeds" between Columbia and RCA, who introduced 33- and 45-rpm records, respectively, [12] opened the field to component makers by disturbing consumer perceptions of the existing paradigm. This was soon reinforced in the early 1950s by even more options, such as tape recorders [21, p. 350]. Listeners who took fidelity seriously now bad a wide choice of equipment.

The importance of compatibility

Compatibility among the range of options was developed through the market as component manufacturers were forced to cooperate, at least up to a point, in order to be able to sell their products at all. Many promoters of high-quality components could not interest established producers and were forced to enter manufacturing themselves and to market directly to the public. Separate stores for high-fidelity and later stereo equipment developed in which customers could hear various combinations before deciding [21, pp. 351–352]. Only components that were compatible could be demonstrated. Similarly, the growth of the kit industry relied on interchangeability. Moreover, as many of the best components were developed in Britain or on the Continent, international standards became common. [13]

The origins of 33-rpm records

The first mass-produced disks with a reasonable range of fidelity, Decca's Full Frequency Range Recordings (FFRR), appeared originally on the 78-rpm format. The introduction of long-playing 33-rpm records and 45-rpm singles, however, provided a major impetus behind the devel-

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[11] For the famous case of one such listener, the possessor of "a 'golden ear' of the richest sheen," see [7, October 1946, p. 161].

[12] Columbia's offered a 33-rpm attachment in 1948, and RCA placed its 45-rpm rapid-drop changer on the market in the following year.

[13] Garrard, for instance, used different-sized flywheels for the American and European markets to allow for local differences in the number of cycles per second in electricity transmission. Otherwise, the same record changers were compatible with other components everywhere.

opment of high-fidelity reproduction. As the maximum playing time per side for a 12-inch 78 was barely five minutes, longer classical works required several disks and were frequently disrupted, sometimes in mid-movement. In addition, the quality of sound available on 78s produced from a shellac mixture was poor. In 1932, therefore, RCA introduced 33-rpm records made of vinyl, which reduced surface noise. The RCA records featured grooves that were only a little narrower than standard 78 grooves, however, which limited 33-rpm playing times to only around twice that of 12-inch 78s. More importantly, the wide grooves required wide styli and heavy pickups, which cut through the soil vinyl after the records had been played a few times. RCA did not address these hardware problems. Because of the scarcity of suitable turntables and the fragility of the records, RCA terminated the experiment the following year [29, p. 57; 21, pp. 339–340].

Networks in hardware and software

Following World War II, Columbia decided to reintroduce 33-rpm vinyl records. In order to increase playing time and (literally) reduce the wear and tear on vinyl, Columbia engineers concentrated on 1-mil microgrooves that could be used with a lighter stylus and pickup. Narrower grooves provided only part of the solution, however, as long as they were spaced as far apart as 78-rpm grooves of shellac-based records. As late as 1946, Columbia could provide only 11 to 12 minutes per side. To determine the desired length, Wallerstein surveyed the classical repertoire and found out that, with 17 minutes per side, 90 percent bf classical pieces would fit on a single two-sided disk. By approximately doubling the number of grooves to between 190 and 225 per inch, Columbia engineers were soon able to exceed the 17-minute standard, and the firm decided to market 33-rpm long-playing records from the fall of 1948 [29, pp. 57–58; 21, p. 340].

Columbia recognized, of course, that simply offering the records would not be sufficient. Easy availability of 33-rpm record players would also be required. As Columbia, in contrast to RCA, did not itself manufacture electrical equipment, the success of the LP (a Columbia trademark) depended on convincing one or more outside firms to manufacture players. Recalling RCA's success with the Duo Jr. record player in 1933, Columbia approached several existing manufacturers to develop an inexpensive 33-rpm player. The company picked Philco as the initial supplier, with Columbia providing much of the basic technology. Wallerstein's recognition of the importance of networks was shown by his initial disappointment that only a single player manufacturer was chosen. "I was a little unhappy about this, because I felt that all of the manufacturers should be making a player of some sort – the more players that go on the market, the more records could be sold" [29, p. 58].

The price of the Philco "attachments" was soon reduced from $29.95 to $9.95, the cost at which Philco supplied them to Columbia. Columbia was able to leave the attachment business within a year as other manufacturers followed Philco's lead [29, p. 61].

Columbia also realized the importance of networks of competitors. Recognizing that it would prosper if other recording companies adopted the 33-rpm microgroove standard, it offered to license the process, a proposition that was quickly taken up by other, smaller, companies. Buyers of classical records responded to the convenience of the LP, the alleged unbreakability of vinyl disks (which RCA had begun to market as 78s in 1946), and the sharp reduction in price. Moderate-length classical works such as Beethoven's Fifth Symphony, which had previously required four 78-rpm records selling for $2 each, now appeared on a single LP at a fraction of the cost [29, pp. 58,60; 21, pp. 339–430; 7, September 1939, p. 100]. Given the high price-elasticity of records, the lower price of LPs permitted an important broadening of the repertoire, which reinforced the density of the network and further encouraged consumers to switch to the new standard.

Thus, although there were no basic patents covering the LP process, Columbia was able to appropriate a large share of the profits by positioning itself as the leading firm in the network of competitors. Other firms that joined the network also prospered, but those that initially held out lost heavily and were eventually forced to conform. RCA, for example, lost $4.5 million on records between June 1948 and January 1950, when it began to issue its own LPs. Its classical sales were decimated, and a number of its most important artists, including Pinza, Rubinstein, and

Heifetz, either deserted or threatened to do so. Over the same period, Columbia cleared $3 million [29, pp. 60–61].

RCA's response

RCA's first approach to the threat of the LP was to try to block the network by establishing its own incompatible system. Columbia had considered issuing six- or seven-inch 33-rpm records for the large singles market, but abandoned the idea. This left an opening for RCA, which introduced 45-rpm singles and produced its own record players and phonographs. In order to forestall competition, RCA chose to use a larger spindle that could not accommodate 33 (or 78) records [29, pp. 60–61; 21, pp. 340–342]. Although other companies followed RCA with large-hole 45s, however, the incompatibility turned out to be in one direction only, since 45-rpm records could easily be fitted in the center with a metal or plastic disk that permitted use with a standard spindle. [14] Moreover, the 45-rpm microgrooves could be played with a stylus designed for 33-rpm records. In the end, RCA was unable to develop a proprietary hardware system fed by its own software variation. Even though the seven-inch 45-rpm format became the standard for singles, 12-inch 33-rpm LPs captured the market for longer works ad collections. RCA eventually joined independent manufacturers in producing phonographs and turntables that operated at all of the major speeds (including 78 rpm) and provided two styli (one for 78 rpm and one for 33- and 45-rpm microgrooves).

The importance of networks to the adoption of the LP and FM

The rapid spread of 33- and 45-rpm record formats contrasts sharply with the long delays required for FM receivers to become a vital part of high-fidelity systems. The use of frequency, rather than amplitude, modulation of radio signals and of very-high-frequency (VHF) waves for transmission permits reductions in atmospheric and man-made interference; relative immunity from other stations operating on the same frequency; and better fidelity of reproduction, especially in regard to dynamic volume range and frequency response. Despite these advantages, FM transmission spread slowly following its introduction in the United States in 1940. The number of FM stations actually fell significantly in the early 1950s, and as late as 1975 the FM share of the total radio listening audience was only 30 percent, as opposed to 75 percent in 1988 [10; 26].

The principal reason that purchasers of high-fidelity components were converted to LP turntables so quickly but resisted the charms of FM tuners for almost two decades was that LPs offered such important advantages when compared to 78 rpm records that a software network was created almost immediately, which consumers were then able to take advantage of through a series of individual purchases of relatively inexpensive record players and phonographs. The great majority of radio listeners, however, could see no immediate technical advantage in investing in FM equipment because popular music, in contrast to classical, had a limited dynamic range during the early decades of FM broadcasting. Moreover, radio listeners had less control because they were dependent on a network with two stages: the records and the stations that transmitted them. When the dynamic range of popular music broadened in the late 1950s and then stereo multiplex became available, the interests of popular- and classical-music listeners merged. Only at this point did the market become dense enough to justify greater investment by broadcasters in FM programming. The interests of FM consumers and producers therefore both evolved, but each faced its own bottlenecks that had to be overcome before further progress was possible.

From modular systems to appliances?

More recent developments, including cassette recorders and CD players, have strengthened the old principle of attaching new options to existing systems. After more than four decades of development, however, it is possible that high sophistication is no longer of much value to the consumer. According to one estimate, 80 percent of listeners are "rather deaf" at ranges above 10,000 Hz. Casual empiricism also suggests that many

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[14] In the terminology of David and Bunn [4], the RCA system was susceptible to a unidirectional "gateway technology."

listeners prefer extra volume to better tone when playing music.

In contrast to microcomputers, stereo equipment serves only one basic use: the reproduction of sound. New components represent variations on a theme rather than departures into new realms. Except for the most golden of ears or snobs, the point has probably been reached at which packaged systems [15] by such firms as Pioneer and Sony meet all reasonable technical specifications. At this mature stage of the product life cycle, the transaction costs of choice for most consumers may outweigh the benefits arising from picking and choosing. Preset packages cover almost the entire product space, not because consumers demand an undifferentiated no-frills product analogous to the Model T, but because with maturity a standardized product has become so well developed that it now meets the needs of almost all users. It remains to be seen whether a new era of modularity will emerge when, as is often predicted, stereo systems become more integrated into video and computer networks.

The microcomputer industry

Early developments

The first microcomputer is generally acknowledged to have been the MITS/Altair, which graced the cover of *Popular Electronics* magazine in January 1975. [16] Essentially a microprocessor in a box, the machine was built around the Intel 8080 chip. Its only input/output devices were lights and toggle switches on the front panel, and it came with a mere 256 bytes of memory. But the Altair was, at least potentially, a genuine computer. Its potential came largely from a crucial design decision: the machine incorporated a number of open "slots" that allowed for additional memory and other devices to be added later. These slots were hooked into the microprocessor by a network of wires called a "bus," which came to be known as the S-100 bus because of its 100-line structure.

Add-ons – especially memory boards – were definitely the first bottleneck of the Altair system. Very quickly, third-party suppliers sprang up, many of them literally garage-shop operations. Using a microcomputer, especially a primitive early model, required some less-tangible complementary activities as well: software and know-how. Both of these gaps were filled exclusively by third parties, the latter by grass-roots organizations called user groups. In effect, the machine was captured by the hobbyist community and became a truly open modular system. Like most manufacturers, the Altair's designers wanted to keep the system as proprietary as possible. But when they tried to tie the sale of some desirable software to the purchase of inferior MITS memory boards, the main result was the dawn of software piracy. Moreover, the first clone of the Altair – the IMSAI 8080 – appeared within a matter of months.

The early success of MITS, IMSAI, and others anchored the popularity of the 8080/S-100 standard, especially among hobbyists, who were still the primary buying group. Lee Felsenstein, the influential leader of the Homebrew Computer Club in Northern California, argued that the standard had reached "critical mass," and, sounding like a present-day theorist of network externalities, forecast the demise of competing chips and buses [17, p. 123]. The main reason was the impressive library of software that S-100 users had built up.

The Apple II

The predicted dominance of the S-100 (and the CP/M operating system it used) never materialized. In 1977, three new machines entered the market, each with its own proprietary operating system, and two using an incompatible non-Intel microprocessor. The Apple II, the Commodore PET, and the Radio Shack TRS-80 Model I quickly outstripped the S-100 machines in sales and, by targeting users beyond the hobbyist community, moved the industry into a new era of growth.

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[15] Although these systems are sold as entities, most are in fact composed of separate components manufactured by a single firm. When they do not include the full range of options such as CD players, they usually offer provisions for plug-in sets for buyers who wish to diversify later.

[16] For a much longer and better-documented history of the microcomputer, see [13], on which this section draws. A condensed version of this case study also appears in [12].

The most important of the three machines was the Apple II. Apple Computer had been started a year earlier by Stephen Wozniak and Steven Jobs, two college dropouts and tinkerers. The hobbyist Wozniak insisted that the Apple be an expandable system with slots and that technical details be freely available to users and third-party suppliers. Jobs saw the Apple as a single-purpose product, and he objected to the slots as unnecessary. Fortunately for Apple, Wozniak won the argument, and the Apple II contained eight expansion slots. Unlike the hobbyist S-100 machines, however, it was compact, attractive, and professional, housed with its keyboard in a smart plastic case.

With early revenues coming almost entirely from sales of the Apple II, the company took in three quarters of a million dollars by the end of fiscal 1977; $8 million in 1978; $48 million in 1979; $117 million in 1980 (when the firm went public); $335 million in 1981; $583 million in 1982; and $983 million in 1983. With the development of word processors like WordStar, database managers like dBase II, and spreadsheets like VisiCalc, the machine became a tool of writers, professionals, and small businesses. And, because of its slots, it could accommodate new add-ons – and therefore adapt to new uses – as they emerged.

Modularity again: the IBM PC

By mid 1981, the uses of the microcomputer were becoming clearer than they had been only few years earlier, even if the full extent of the product space lay largely unmapped. A microcomputer was a system comprising a number of more-or-less standard elements: a microprocessor unit with 64K bytes of RAM memory; a keyboard, usually built into the system unit; one or two disk drives; a monitor; and a printer. The machine ran operating-system software and applications programs like word processors, spreadsheets, and database managers. CP/M, once the presumptive standard, was embattled, but no one operating system reigned supreme.

One response to this emerging paradigm was the bundled transportable computer – like the Osborne and later the Kaypro – that packaged together most of the basic hardware and software into an inexpensive package. These machines achieved a modicum of success. But the signal event of 1981 was not the advent of the cheap bundled portable. On 12 August 1981, IBM introduced the computer that would become the paradigm for most of the 1980s. Like the Osborne and Kaypro, it was not technologically sophisticated, and it incorporated most of the basic features users expected. But, unlike the bundled portables, the IBM PC was a system, not an appliance: it was an incomplete package, an open box ready for expansion, reconfiguration, and continual upgrading.

In order to introduce quickly a PC bearing its own nameplate, IBM embarked on an uncharacteristic strategy. Rather than building the machine inhouse, as was typical for IBM's large computers, the company produced the PC almost entirely by assembling parts bought on the market. Moreover, to save time, the design team followed the open architecture of the S-100 machines and initially resisted the temptation to produce its own add-ons.

The emergence of a network of competitors

Because the machine used the Intel 8088 instead of the 8080, the PC needed a new operating system. IBM wanted its system to become dominant in the industry. But, despite a long attachment to the proprietary strategy in mainframes, the company contracted out the design of the software, and, in a bold move, allowed Microsoft, the contractor, to license MS-DOS (as the operating system was called) to other manufacturers. One result was a legion of clones that offered IBM compatibility, generally at a price lower than IBM charged. But the other result was that MS-DOS – and the IBM PC's bus structure – did indeed become the new industry standard. Makers of IBM-incompatible machines went out of business, converted to the new standard (like Tandy and Kaypro), or retreated to niche markets (like Commodore and Apple, even if the latter's niche is quite roomy).

IBM did have one trick up its sleeve to try to ward off cloners, but it turned out not to be a very powerful trick. The operating system that Microsoft designed for the IBM PC – called PC-DOS in its proprietary version – differs slightly in its memory architecture from the generic MS-DOS IBM allowed Microsoft to license to others. IBM chose to write some of the

BIOS (or basic input–output system, a part of DOS) into a chip and to leave some of it in software. They then published the design of the chip in a technical report, which, under copyright laws, copyrighted part of the PC-DOS BIOS. IBM sued Corona, Eagle, and a Taiwanese firm for infringing the BIOS copyright in their earliest models. These companies, and all later cloners, responded, however, with an end run. They contracted with outfits like Phoenix and AMI to create a BIOS that does what the IBM BIOS does, but does it in a different way. This removed the principal proprietary hurdle to copying the original PC.

What is especially interesting is the diversity of sources of these compatible machines. Many come from American manufacturers like Compaq and Tandy, who sell under their own brand names. Another group would be foreign manufacturers selling under their own brand names. The largest sellers are Epson and NEC of Japan and Hyundai of Korea, but there is also a large OEM (original-equipment manufacturer) market, in which firms – typically Taiwanese or Korean, but sometimes American or European – manufacture PCs for resale under another brand name. Perhaps the most interesting phenomenon is the no-name clone – the PC assembled from an international cornucopia of standard parts and sold, typically, through mail orders. Most manufacturers, even the large branded ones, are really assemblers, and they draw heavily on the wealth of available vendors. But the parts are also available directly, and it is in fact quite easy to put together one's own PC from parts ordered from the back of a computer magazine. By one 1986 estimate, the stage of final assembly added only $10 to the cost of the finished machine – two hours work for one person earning about $5 per hour. As the final product could be assembled this way for far less than the going price of name brands – especially IBM – a wealth of backroom operations sprang up. The parts list is truly international. Most boards come from Taiwan, stuffed with chips made in the U.S. (especially microprocessors and ROM BIOS) or Japan (especially memory chips). Hard-disk drives come from the United States, but floppy drives come increasingly from Japan. A power supply might come from Taiwan or Hong Kong. The monitor might be Japanese, Taiwanese, or Korean. Keyboards might come from the U.S., Taiwan, Japan, or even Thailand.

The importance of the network

It is tempting to interpret the success of the original IBM PC as merely the result of the power of IBM's name. While the name was no doubt of some help, especially in forcing MS-DOS as a standard operating system, there are enough counter examples to suggest that it was the machine itself – and IBM's approach to developing it – that must take the credit. Almost all other large firms, many with nearly IBM's prestige, failed miserably in the PC business. The company that Apple and the other early computer makers feared most was not IBM but Texas Instruments, a power in integrated circuits and systems (notably electronic calculators). But TI flopped by entering at the low end, seeing the PC as akin to a calculator rather than as a multipurpose professional machine. When TI did enter the business market in the wake of the IBM PC, its TI Professional also failed because the company refused to make the machine fully IBM compatible. Xerox entered the market with a CP/M machine that – in 1981 – was too little too late. Hewlett-Packard was also slow out of the blocks.

Consider, in particular, the case of Digital Equipment Corporation [23]. DEC is the second-largest computer maker in the world, and the largest maker of minicomputers. In 1980, the company decided to enter the personal computer business. The Professional series was to be the company's principal entry into the fray. It would have a proprietary operating system based on that of the PDP-11 minicomputer; bit-mapped graphics; and multitasking capabilities. But, despite winning design awards, the computer was a commercial flop. All told, the company lost about $900 million on its development of desktop machines. DEC's principal mistake was its unwillingness to take advantage of external economies. The strategy of proprietary systems and inhouse development had worked in minicomputers: put together a machine that would solve a particular problem for a particular application. The PC is not, however, a machine for a particular application; it is a machine adaptable to many applications – including some its users had not imagined when they bought their machines. Moreover, DEC underrated the value of software. And, unlike IBM, DEC chose to ignore existing third-party capabilities. Except for the hard disk and the line cord, DEC designed and built every piece of the Professional.

The importance of modularity

Why were the most successful machines – the Apple II and the IBM PC – also the most modular? Microcomputer software is a popular example of the importance of network externalities. The value of owning a computer that runs a particular kind of software (IBM-compatible software under MS-DOS, for example) is dependent on the number of other people who own similar machines, since the amount of software available is proportional to the total installed base of computers that can use that kind of software. But although this is certainly part of the story, its impact is less than might have been expected because the development of software networks has turned out to be a cheaper and more flexible process than was originally envisaged. By the summer of 1980, Microsoft had in place a system of software development in which code was first written in "neutral" language on a DEC minicomputer and then run through a translator program that would automatically convert the neutral software into the form needed by a specific machine. This made it possible to write machine-independent software. Now, smaller companies without this facility would still be tempted to write software specifically for one machine first, and the system with the largest installed base would offer the greatest temptation. But there are profits to be made writing or adapting software for even idiosyncratic machines, and a cottage industry like software development is particularly likely to seize such opportunities.

The explanation for modularity in microcomputers – modularity in hardware as well as software – is broader than, albeit related to, the phenomenon of network externalities. As we argued above, the benefits of modularity can appear on both the demand side and the supply side.

Demand-side benefits

In microcomputers, the economies of scale of assembling a finished machine are relatively slight. The machines are user-friendly in comparison with their larger cousins, and ample information is available through books, magazines, and user groups. There is also a lively middleman trade in the industry, revolving around so-called value-added resellers, who package hardware and software systems to the tastes of particular non-expert buyers. At the same time, the uses of the microcomputer are multifold, changing, and, at least in the early days, were highly uncertain. A modular system can blanket the product space with little loss in production or transaction costs.

Moreover, the microcomputer benefited from a kind of technological convergence, in that it turned out to be a technology capable of taking over tasks that had previously required numerous distinct – and more expensive – pieces of physical and human capital. By the early 1980s, a microcomputer costing $3,500 could do the work of a $10,000 stand-alone word processor, while at the same time keeping track of the books like a $100,000 minicomputer and amusing the kids with space aliens like a 25-cents-a-game arcade machine.

Supply-side benefits

On the producer side, again, a decentralized and fragmented system can have advantages in innovation to the extent that it involves the trying out of many alternate approaches simultaneously, leading to rapid trial-and-error learning. This kind of innovation is especially important when technology is changing rapidly and there is a high degree of both technological and market uncertainty. That the microcomputer industry partook of external economies of learning and innovation is in many ways a familiar story that need not be retold. Popular accounts of Silicon Valley sound very much like Marshall's localized industry in which the "mysteries of the trade become no mysteries; but are as it were in the air, and children learn many of them unconsciously" [15, IV.x.3, p. 225]. Compare, for example, Moritz's discussion of the effect of Silicon Valley culture on one particular child: Wozniak. "In Sunnyvale in the mid-sixties, electronics was like hay fever: It was in the air and the allergic caught it. In the Wozniak household the older son had a weak immune system" [17, p. 29]. One could easily multiply citations. This learning effect went beyond the background culture, however. It included the proclivity of engineers to hop jobs and start spinoffs, creating a pollination effect and tendency to biological differentiation that Marshall would have appreciated.

Also, as we suggested earlier, innovation in a modular system typically proceeds in autonomous fashion, taking advantage of the division of labor. So long as it maintains its ability to connect to a standard bus, an add-on board can gain in capabilities over a range without any other parts of the system changing. Graphics boards can become more powerful, modems faster, software more user-friendly, and pointing devices more clever. The prime focal points of this innovation are often technological "bottlenecks," in this case bottlenecks to the usefulness of the microcomputer in meeting the many needs to which it has been put. The lack of reliable memory boards was a bottleneck to the usefulness of the early Altair. The 40-column display and the inability to run CP/M software were bottlenecks of the Apple II. The IBM PC's 8088 microprocessor could address only a limited amount of internal memory. All of these – and many more – were the targets of innovation by third-party suppliers, from Cromemco and Processor Technology to Microsoft and Intel. Sometimes a bottleneck is not strictly technological, as when IBM's copyrighted ROM BIOS became the focus of inventing-around by firms like Phoenix and AMI. Although "innovations" of this sort may not directly yield improvements in performance, they do help to keep the system open. In a wider sense, we can also include as bottleneck-breakers those innovations that extended the system's abilities in new directions – modems, machinery-controller boards, facsimile boards, graphics scanners, etc. The microcomputer as a modular system has also partaken of certain types of integrative innovations, that is, innovations that allow a single device to perform functions that had previously required several devices. A good example of this would be the chip set designed by Chips and Technologies to integrate into a few ICs 63 of the 94 circuits on the original IBM AT, thus greatly facilitating the making of clones.

Other types of networks and systems

So far the discussion has been couched in terms of user/assemblers. But the analysis also applies to intermediate products where consumers are often even more sophisticated and well-informed about product attributes than typical final consumers.

The early history of the automobile industry provides an instructive example of the purposes and limitations of decentralized networks. [17] Recognition of the value of networks and external economies resulted in an important agreement in 1910: Sponsored by the Society of Automotive Engineers, it led to the establishment of a set of standards for component parts. In the early period of the industry, most independent suppliers built to specifications laid down by the assembler. As a result, there were more than 1,600 types of steel tubing used and 800 standards of lock washer, with a similar proliferation of varieties of other components (Epstein [6, pp. 41–3]). Early attempts to set common standards had been unsuccessful, but the panic of 1910 brought a crisis among assemblers. The failure of suppliers in the panic emphasized the vulnerability of small assemblers who were not readily able to switch to other firms because of peculiarities in specifications. Led at first by Howard E. Coffin of the Hudson Motor Car Company, over the next decade S.A.E. set detailed standards for numerous parts, in the process creating interchangeability across firms. After standardization, for example, the number of types of steel tubing had been reduced to 210 and the number of lock washers to 16. Throughout the initial period of standardization, until the early 1920s, most interest was shown by the smaller firms, who had the most to

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[17] Although they were not final consumers, the smaller automobile assemblers were in a position analogous to W_1, W_2, and W_3 in fig. 5 in that, for many components, they could not individually use the total output of a supplier operating at MES. As a result, the smaller assemblers tended to purchase components from outside firms that, to achieve efficiency, also needed to supply competing assemblers. This, of course, increased the commercial attractiveness of compatibility of components across assemblers and was also consistent with the delegation of a degree of component design to the suppliers.

The larger automobile assemblers, however, were more frequently able to absorb the entire production of their suppliers and were, therefore, in a position similar to that of P in fig. 4. Alternatively, they were well placed to integrate vertically if their sources of supply were inadequate or under threat. Thus the large assemblers were less interested in compatibility.

gain. The larger firms such as Ford, Studebaker, Dodge, Willys-Overland, and General Motors tended to ignore the S.A.E. and relied instead on internally established standards (Thompson [28, pp. 1–11]).

Similar behavior has been common in other industries. Beginning in 1924, for example, radio manufacturers established a variety of standards committees to allow greater interchangeability and embed themselves in a decentralized network (Graham [8, p. 40.]). A more recent case is the ongoing debate among semiconductor fabricators and equipment manufacturers over the Modular Equipment Standards Architecture (MESA) [32, p. 26]. Here a consortium of equipment makers is pushing for an open control and interface protocol that will allow semiconductor fabricators to mix and match equipment from many different suppliers on a single assembly line. This movement stands in opposition to Applied Materials, Inc., the largest maker of "monolithic," or non-distributed, fabrication systems, which is trying to use its large installed base to leverage a more open version of its Precision 5000 system as the industry standard.

Conclusions

There are a number of striking similarities between the cases of high-fidelity and stereo systems and microcomputers. These similarities in turn illustrate a number of theoretical points.

In both cases, first of all, the industry adopted a modular structure with a common standard of compatibility rather than a structure of competing prepackaged entities. In both cases, large firms tried the appliance approach in an effort to appropriate the rents of innovation. But these attempts ultimately failed, and companies who relied heavily on an external network of competitors and suppliers were clearly more successful. Columbia encouraged the production of 33-rpm records and players, and IBM allowed Microsoft to license MS-DOS widely. These firms became significant players in networks that were not under their control, thereby garnering larger payoffs than if they had attempted to market a proprietary product. Teece [27] has suggested some ways in which the desire to appropriate the rents of innovation can lead to vertical integration. These cases suggest the opposite possibility, in which the same desire can lead to vertical (and horizontal) *disintegration*.

In both cases, aficionados and enthusiasts, with more sophisticated tastes and a higher willingness to pay, played an important role in edging the systems onto a modular path. These hobbyists and audiophiles tested the limits of the systems and helped identify the bottlenecks that became foci of innovation. In many cases, these individuals set up in business to supply (and typically improve) the bottleneck components.

In both cases, one driving issue was the compatibility of hardware and software. Cast in these terms, the story revolves around the much-discussed phenomenon of network externalities leading to technological "lock in" (David and Bunn [4]). What has not been stressed in the literature, however, is the modular nature of these systems. Quite apart from any network externalities, the modularity of stereo and microcomputer systems allowed producers to participate in a system that was better able to blanket the product space – and thereby generate greater consumer demand – than a system of competing prepackaged entities.

There is perhaps a message in this for the debate over competitiveness and industrial policy: namely, that the definition of the "product" matters. As we argued above, vertical integration may have its benefits (or at least relatively few disbenefits) for the production of components fitting into the system. This is because compatibility within the component is unnecessary, and a vertically integrated firm may have some advantages in coordinating systemic innovation of the internal subcomponents of the module. But large size and vertical integration are of little benefit in coordinating across the compatibility boundaries of the larger system. Especially in the early stages of development, experimentation is a much more important concern than coordination. And rapid trial-and-error learning is one forte of a decentralized network.

There is evidence that stereo systems, and even microcomputers to some extent, have matured to an extent that they are becoming more like appliances. Because of technological progress and learning about demand, a standard system can now meet the needs of a large fraction of users without modification. But it is dangerous to extrapolate trends too far. For example, the home-entertainment industry may be entering a new phase of change, as convergence with computer and video technology opens up new possibilities for the consumer. The home-entertainment system today no longer produces merely sound but also video, with the monitor and video-cassette recorder tied into the system and capable of high-fidelity stereo sound. Technological convergence with the microcomputer is already occurring in the case of the compact-disk player, which uses basically the same technology in its guises as audio source and data source. Many audio and video products now include microprocessors, and can be programmed in limited ways. If the predictions of the popular press hold true, further convergence will take place with the advent of computer-interactive audio and video and high-definition television.

Indeed, one might speculate in general that modular systems are likely to take on greater importance in the future. This is so for two reasons. First of all, the predicted advent of flexible manufacturing would reduce the cost advantages of large production runs. This would in turn reduce the advantages of integrating the functions of assembly and packaging. Second, a continued increase in consumer incomes would mean more sophisticated tastes and a greater relative demand for the finely tuned products a modular system permits.

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